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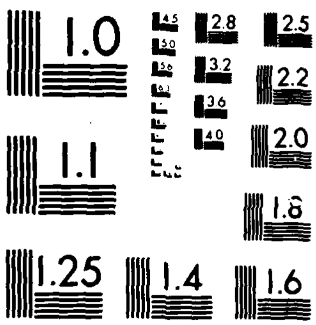

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FINAL REPORT

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Office of Naval Research

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STRUCTURE AND MIXING IN TURBULENT SHEAR FLOWS

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SUMMARY

The research problems studied under this contract were the following:

1. Mixing in a forced plane shear layer
2. Turbulent structure in two dimensional far wakes
3. Effect of external excitation on separated flow
4. Effect of curvature on free-shear-layer structure and mixing
5. Structure and mixing in transverse jets.

Significant results obtained are briefly summarized in the following Discussion. Complete descriptions of the research and of the results are contained in the references cited.

DISCUSSION

1. Mixing in a Forced Plane Shear Layer. Large scale structure and mixing processes were investigated in chemically reacting wakes and shear layers to which a periodic disturbance was applied. The experiments employed a diffusion-limited acid-base reaction to directly measure the extent of mixing. Optical diagnostics used included laser absorption and laser induced fluorescence. Absorption of laser light by reacted product provided a measure of cross-stream average product. Fluorescence was measured by a self-scanning linear photodiode array using high speed computer data acquisition to obtain the product distribution across the layer.

Previous results showing that forcing alters the structure and growth rate of shear layers were confirmed. Forcing artificially extends the lifetime of vortices whose spacing equals the disturbance wavelength.

Amalgamation of smaller vortices is enhanced over that in the natural layer until the frequency locked size is achieved. At high Reynolds number product measurements show reduction of product with forcing. At moderate Reynolds numbers, on the other hand, there is an increase in product when forced. In one case, a five fold increase in product was observed. The differences are related to the different effects of forcing on entrainment, composition ratio and secondary structure.

A dramatic, order of magnitude, increase in mixing was discovered for certain forced wake flows. This effect is strongly associated with an interaction between the spanwise organized wake vortices and the test-section side walls.

References

Roberts, Frederick A. 1984 "Effects of a Periodic Disturbance on Structure and Mixing in Turbulent Shear Layers and Wakes". Ph.D. Thesis, California Institute of Technology.

Roberts, F.A. and Roshko, A. 1985 "Effects of Periodic Forcing on Mixing in Turbulent Shear Layers and Wakes". AIAA Shear Flow Control Conf., 12-14 Mar., Boulder, Co., AIAA-85-0552.

2. An Experimental Study of Large Structure in the Far Wakes of Two-dimensional Bluff Bodies. Smoke-wire flow visualization and hot-wire anemometry were used to study near and far wakes of two-dimensional bluff bodies. For the case of a circular cylinder at $70 < Re < 2000$, a very rapid (exponential) decay of velocity fluctuations at the Karman vortex street frequency is observed. Beyond this region of decay, larger-scale (lower wave-number) structure can be seen. In the far wake (beyond one hundred diameters) a broad band of frequencies is selectively amplified and then damped, the center of the band shifting to lower frequencies as downstream distance is increased.

The far-wake structure does not depend directly on the scale or frequency of the original Karman vortices; the growth of this structure is due to hydrodynamic instability of the developing mean wake profile; it is not caused by amalgamation of the Karman vortices. Under certain conditions amalgamation can take place, but is purely incidental, and is not the driving mechanism responsible for the growth of larger-scale structure. Similar large structure is observed downstream of porous flat plates (Re ~ 6000), which do not initially shed Karman-type vortices into the wake.

Hot-wire measurements showed that two-dimensional locally-parallel inviscid linear stability theory is adequate to explain the growth of downstream structure. Namely, measured prominent frequencies in the cylinder wake are in close agreement with those predicted by the theory, when streamwise growth of wake width is taken into account.

Development of three-dimensionality in the far wake of a circular cylinder was also briefly investigated, using smoke-wire flow visualization.

References

Cimbala, John Michael 1984 "Large Structure in the Far Wakes of Two-Dimensional Bluff Bodies". Ph.D. Thesis, California Institute of Technology.

Cimbala, J., Nagib, H. and Roshko, A. 1985 "Large Structure in the Far Wakes of Two-Dimensional Bluff Bodies". Submitted to J. Fluid Mechanics.

3. Controlled Excitation of a Reattaching Flow. An experimental study was made of the effect of a periodic velocity perturbation on the separation bubble downstream of the sharp-edged blunt face of a circular cylinder aligned coaxially with the free stream. Velocity fluctuations were produced with an acoustic driver located within the cylinder and a

small circumferential gap located immediately downstream of the fixed separation line to allow communication with the external flow. The flow could be considerably modified when forced at frequencies lower than the initial Klevin-Helmholtz frequencies of the free shear layer, and with associated vortex wavelengths comparable to the bubble height. Reattachment length, bubble height, pressure at separation, and average pressure on the face were all reduced. The effects on the large-scale structures were studied on flow photographs obtained by the smoke-wire technique. The forcing increased the entrainment near the leading edge. It was concluded that the final vortex of the shear layer before reattachment is an important element of the flow structure. There are two <u>difference</u> instabilities involved, the Kelvin-Helmholtz instability of the free shear layer and the "shedding" type instability of the entire bubble. A method of frequency scaling is proposed which correlates data for a variety of bubbles and supports an analogy with Karman vortex shedding.

An unsteady and three-dimensional large-scale structure is proposed for the reattachment region of a separation bubble, based on a visualization study of the flow over a plate with a square leading edge. The initial free shear layer structures are primarily two-dimensional but evolve into three-dimensional boundary layer type structures as they near reattachment and interact with the wall. Some segments form "loops" which convect away from the wall and downstream while the spanwise adjacent segments convect toward the wall and upstream. The loops are sometimes clearly arranged in a <u>staggered</u> <u>pattern</u>. Their legs form a series of counter-rotating streamwise vortex pairs which bridge the reattachment zone. These observations reconcile apparently contradictory proposals concerning the fate of the structures as they encounter reattachment.

<u>References</u>

Sigurdson, L.W. and Roshko, A. 1985 "Controlled Unsteady Excitation of a Reattaching Flow". AIAA Shear Flow Control Conf., 12-14 Mar., Boulder, Co., AIAA-85-0552.

Sigurdson, L.W. and Roshko, A. 1984 "The Large-Scale Structure of a Turbulent Reattaching Flow". Bulletin of the American Physical Society, 29, 1542. Providence, R.I.

4. Effects of Curvature on Turbulent Mixing Layers. Experimental studies were conducted in a curved mixing layer in which both the velocity ratio and the density ratio were variable. Flow visualization studies and profile measurements covered a wide range of experimental conditions. The structures observed experimentally were examined in the light of three different instability mechanisms which can exist in the same mean flow.

For the case of mixing layers with uniform density, it was found that the normal large spanwise vortex structures can be weakened or inhibited by Taylor-Gortler instability if the inner stream is faster than the outer stream. For the case of mixing layers with different densities, three-dimensionality is greatly enhanced by Rayleigh-Taylor instability if the inner stream is heavier than the outer stream, and especially if the inner stream is also faster. In the former case the growth rate of the mixing layer was found to be insensitive to changes in the velocity ratio.

The effects of curvature on the structure of the curved turbulent mixing layer were explored in terms of length scales and celerity for the large spanwise structures where these structures could be observed. Other things being equal, the celerity of the large structures was found to depend on density ratio and velocity ratio but not on the sense of the mean streamline curvature.

References

Wang, Chiun 1984 "Effects of Curvature on Turbulent Mixing Layers". Ph.D. Thesis, California Institute of Technology.

5. Transverse Jet Studies. The flow field induced by a jet in incompressible cross-flow was analyzed and the results compared with those

obtained in a reacting water-jet experiment. It is argued that the axial vortex pair in the flow arises from the jet momentum normal to the free stream, the momentum flux being equivalent to a normal force, i.e. to a lift.

A water channel study of the transverse jet ($u_{jet}/u_\infty \sim 10$, $Du_\infty/\nu \sim 3500$), issuing from an orifice on one wall, revealed the presence of intense vortex columns in the wake region. The differences and similarities of this wake with that of a circular cylinder were presented. The vortex columns are seen to extend from the wall well into the main body of the jet and remain quite intense far downstream (even at $16\theta^*$, θ^{*2} = jet momentum flux/free-stream head). These vortices remain strong, apparently due to stretching of the axes as the main jet body penetrates into the free stream. A splitter plate fitted inside the bend of the jet inhibits the formation of the vortex columns. The effect of this wake structure on the mixing characteristics of the jet was investigated by observing the chemical reaction of the jet fluid with the free stream.

References

Broadwell, J.E. and Breidenthal, R.E. 1984 "Structure and Mixing of a Transverse Jet in Incompressible Flow". J. Fluid Mech. 148, 405-412.

Kuzo, D.M. and Roshko, A. 1984 "Observations on the Wake Region of the Transverse Jet". Bulletin of the American Physical Society, 29, 1536.

PERSONNEL

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